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FRACTURE TOUGHNESS ASSESSMENT OF PRESENT AND FUTURE PRESSURE VESSEL MATERIALS BASED ON CHARPY IMPACT ENERGY AND YIELD STRENGTH

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13. ABSTRACT (*Maximum 200 words*)

Several medium and high strength alloys, including AF1410, Inconel 718, PH 13-8 Mo stainless steel, and ASTM A723 high strength low alloy steel, have been heat treated to various strength and toughness levels and evaluated for correlations between fracture toughness and Charpy impact energy. The correlations investigated included those by Rolfe-Novak and Ault-Wald-Bertolo. Previous work by Kapp and Underwood suggests that for A723 steel, the Rolfe-Novak correlation predicts the fracture toughness reasonably well. One potential limitation of their study was that the Charpy impact energy was measured at -40°F, whereas the toughness was evaluated at room temperature. This study evaluates Charpy impact energy and toughness at both room temperature and at -40°F and considers both when utilizing these correlations. Results of this study indicate that the Rolfe-Novak correlation overpredicts the measured fracture toughness at room temperature, and tends to underpredict the measured fracture toughness at -40°F. The Ault-Wald-Bertolo correlation, in all but one instance, was a conservative estimate of the measured fracture toughness of the material at both room temperature and -40°F. Utilizing the results presented in this study, it is recommended that if a correlation is necessary for estimating the toughness of any of these materials, the Ault-Wald-Bertolo correlation will result in a conservative estimate of toughness.

14. SUBJECT TERMS
Fracture Toughness, Charpy Impact Energy, Yield Strength, Rolfe-Novak Correlation, Ault-Wald-Bertolo Correlation, AF1410, Inconel 718, PH13-8 Mo, A723 Steel

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TABLE OF CONTENTS

TABLES

LIST OF ILLUSTRATIONS

INTRODUCTION

Because of the complexities of fracture testing, and the inability of many labs to conduct a fracture toughness test, many labs will simply measure the Charpy impact energy (CVN) and use one of many CVN-K_{Ic} correlations (ref 1) to predict the toughness of the material being investigated. This study examines two well-known correlations that are applicable in the upper-shelf regime. The two correlations studied are the Rolfe-Novak correlation (ref 2)

$$\left(\frac{K_{Ic}}{\sigma_{ys}}\right)^2 = 5\left(\frac{CVN}{\sigma_{ys}} - 0.05\right) \quad (1)$$

and the Ault-Wald-Bertolo correlation (ref 3)

$$\left(\frac{K_{Ic}}{\sigma_{ys}}\right)^2 = 1.37\left(\frac{CVN}{\sigma_{ys}}\right) - 0.045 \quad (2)$$

where σ_{ys} is the 0.2 percent yield strength.

These correlations were developed by compiling a large amount of data and curve-fitting the best linear fit to derive these equations. The Rolfe-Novak study included data from steels with yield strengths in excess of 100 Ksi, while the Ault-Wald-Bertolo study included only ultra-high strength steels (tensile strengths in the range of 200 Ksi to 300 Ksi). Although some of the materials utilized in this study do not fit these classifications, the correlation is still being investigated.

Since the materials being considered all possessed relatively high fracture toughness, even at -40°F, full J-integral (J_{Ic}) fracture toughness tests were conducted according to ASTM E-813, "Standard Test Method for J_{Ic}, A Measure of Fracture Toughness."

Elastic fracture mechanics (K_{Ic}) does not adequately predict the toughness of these materials because we cannot meet the K_{Ic} test requirements, per ASTM E-399, "Standard Test Method for Plane-Strain Fracture Toughness of Metallic Materials." Therefore, we have utilized elastic-plastic fracture mechanics (J_{Ic}) and converted the results to K_J with the following equation:

$$K_J = \sqrt{\frac{EJ_{Ic}}{1-\nu^2}} \quad (3)$$

These K_J values are believed to be good estimates of K_{Ic}.

RESULTS

The results of testing can be observed in Table 1. Note that both CVN and K_J were evaluated at both room temperature (72°F) and -40°F. The data presented in this table are the result of averaging a minimum of three test results for each condition.

The results presented in Table 1 are also shown graphically in Figures 1 and 2. The Rolfe-Novak correlation conservatively predicts the measured fracture toughness of all materials investigated, except for the AF1410. In the case of AF1410, it appears that the Ault-Wald-Bertolo correlation predicts the measured fracture response very accurately.

Figure 3 is significant since it attempts to predict the room temperature fracture toughness response based on -40°F CVN. Again, the Rolfe-Novak correlation does seem to conservatively predict the fracture toughness response (with a few outlier, especially at higher toughness values). As seen in Figure 3, the PH 13-8 Mo stainless steel is not conservatively predicted at room temperature based on a -40°F CVN.

CONCLUSIONS

1. Previous work by Kapp and Underwood (ref 4) indicated that for A723 steel, the Rolfe-Novak correlation predicts the fracture toughness response at room temperature reasonably well based on a -40°F CVN. This study verifies those findings. We have also found that Rolfe-Novak conservatively predicts the room temperature fracture toughness of Inconel 718 and the higher strength levels of AF1410 when based on -40°F CVN. However, the PH 13-8 Mo and the lower strength levels of AF1410 do obey this trend.

2. We have determined that the Rolfe-Novak correlation does not adequately or conservatively predict the fracture toughness at room temperature when estimated by room temperature CVN. Under these conditions, the Ault-Wald-Bertolo correlation does indeed conservatively predict the fracture toughness for all materials investigated.

3. Rolfe-Novak does conservatively predict the -40°F fracture toughness of A723, Inconel 718, and PH 13-8 Mo when based on -40°F CVN. Whereas it does not adequately predict the -40°F fracture toughness of AF1410 when based on -40°F CVN. For this material, the Ault-Wald-Bertolo correlation does predict accurate fracture toughness.

4. Based on the findings of this study, it appears that the accuracy of the two correlations studied is dependent on material tested, heat treatment condition, and test temperature. One general conclusion that can be drawn from this analysis is that the Ault-Wald-Bertolo correlation in most every case studied, conservatively estimated the fracture toughness of each of these materials, heat treatments, and test temperatures. However, the prediction is extremely conservative in many cases. This suggests that whenever an accurate representation of these classes of materials is necessary, a J_{Ic} fracture toughness test must be performed.

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Table 1 - Compilation of strength and toughness data used for analysis

Material	Condition	.2% Y.S. (ksi)	CVN (72F) (ft-lbs)	CVN (-40F) (ft-lbs)	K_J (72F) (lbs/in)	K_J (-40F) (lbs/in)	CVN(72F)/YS (ft-lbs/ksi)	CVN(-40F)/YS (ft-lbs/ksi)	$(K_J\ (72F)/YS)^2$ (in)	$(K_J\ (-40F)/YS)^2$ (in)
AF1410	HT#1	189	69	52	148	104	0.365	0.275	0.613	0.303
	HT#2	219	49	31	186	91	0.224	0.142	0.721	0.173
	HT#3	212	50	33	174		0.236	0.156	0.674	
	HT#4	213	48	40	174	107	0.225	0.188	0.667	0.252
Inconel 718		167	18	18	123	123	0.108	0.108	0.542	0.542
PH 13-8 Mo	HT#5	177	90	68	206	239	0.508	0.384	1.355	1.823
	HT#6	185	60	60	210	237	0.324	0.324	1.289	1.641
A723		168	28	22	118	113	0.167	0.131	0.493	0.452
		115	15	8	61	40	0.130	0.070	0.281	0.121
		155	31	13	100	95	0.200	0.084	0.416	0.376
		149	31	21	109	106	0.208	0.141	0.535	0.506
		117	14	6	57	51	0.119	0.051	0.237	0.190
		160	28	11	102	100	0.175	0.069	0.406	0.391
		148	33	22	107	114	0.216	0.149	0.523	0.593
		185	19	19	102	106	0.103	0.103	0.304	0.328
		153	47	37	131	148	0.307	0.242	0.733	0.936

HT#1	HT#2	HT#3	HT#4	HT#5	HT#6
1650F-1hr,AC	1650F-1hr,AC	1650F-1hr,AC	1650F-1hr,AC	1700F-1hr,AC	1700F-1hr,AC
1525F-1hr,AC	1525F-1hr,AC	1525F-1hr,AC	1525F-1hr,AC	1700F-1hr,AC	1700F-1hr,AC
-100F-1hr,AW	-100F-1hr,AW	-100F-1hr,AW	-100F-1hr,AW	1025F-5hr,AC	1025F-3hr,AC
400F-5hr,AC	925F-5hr,AC	950F-5hr,AC	975F-5hr,AC		

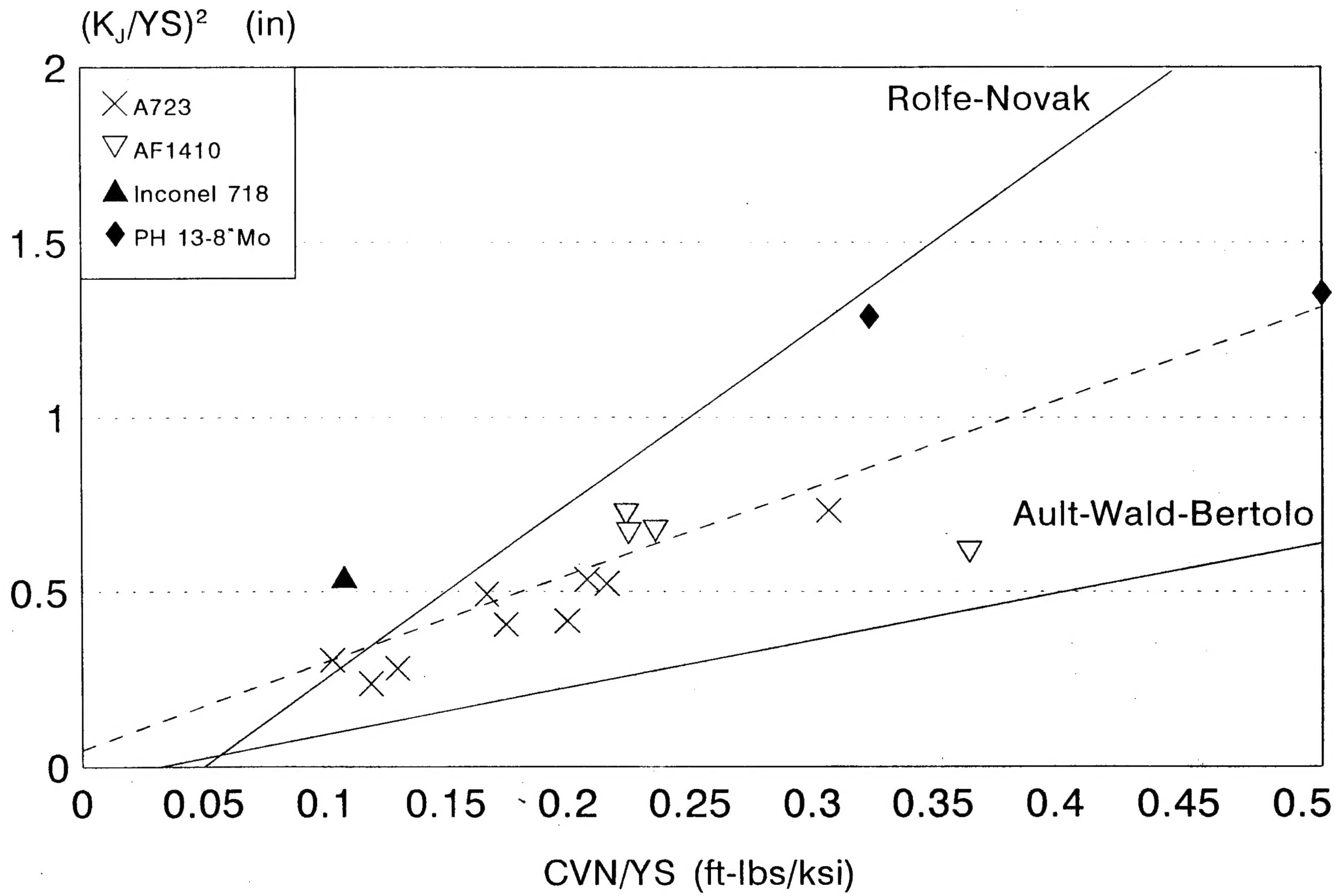

Figure 1 - K_J (72F) vs CVN (72F)
Solid lines represent correlations, dotted lines represent best linear fit of data being studied

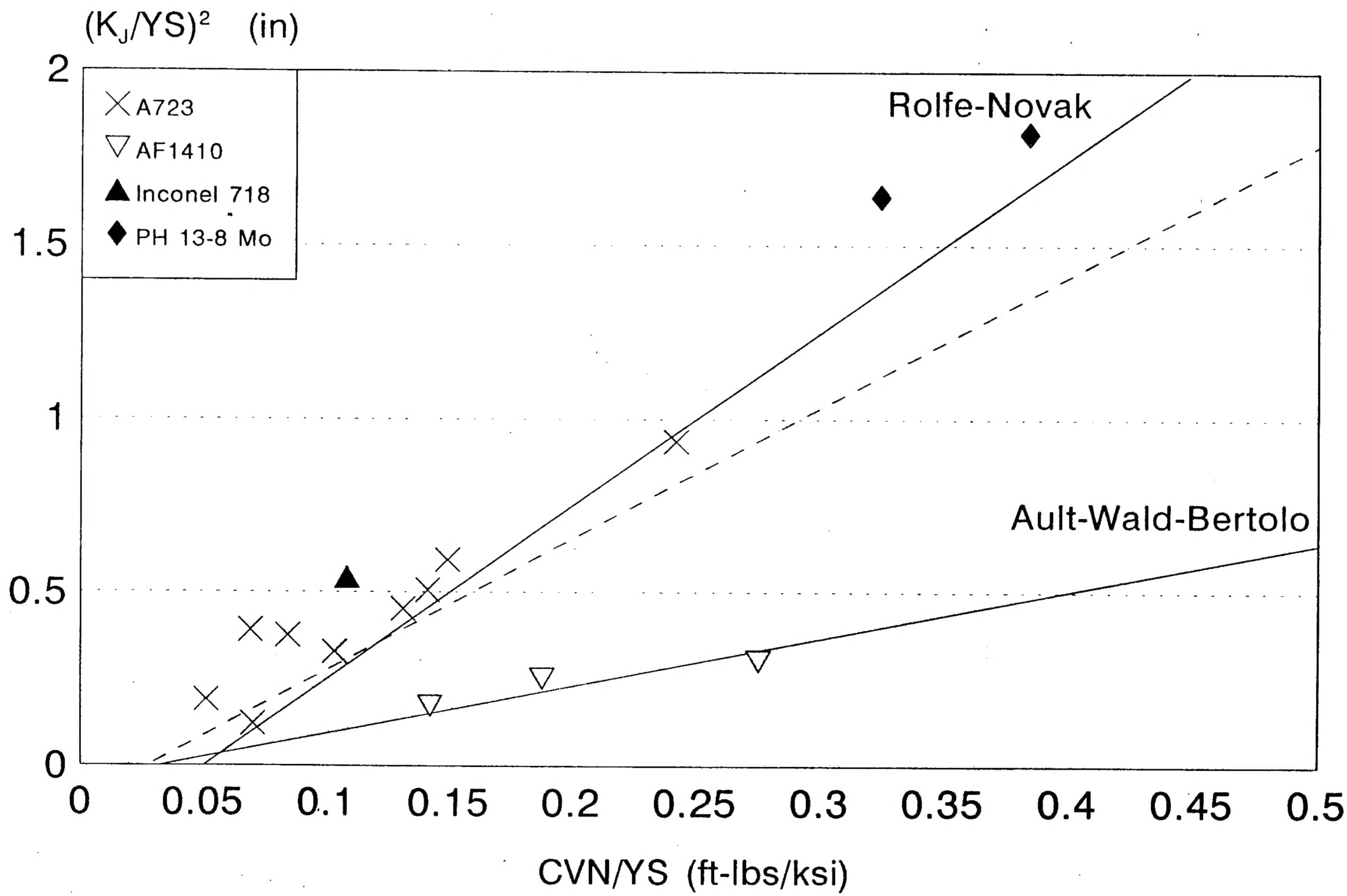

Figure 2 - K_J (-40F) vs CVN (-40F)
Solid lines represent correlations, dotted lines represent best linear fit of data being studied

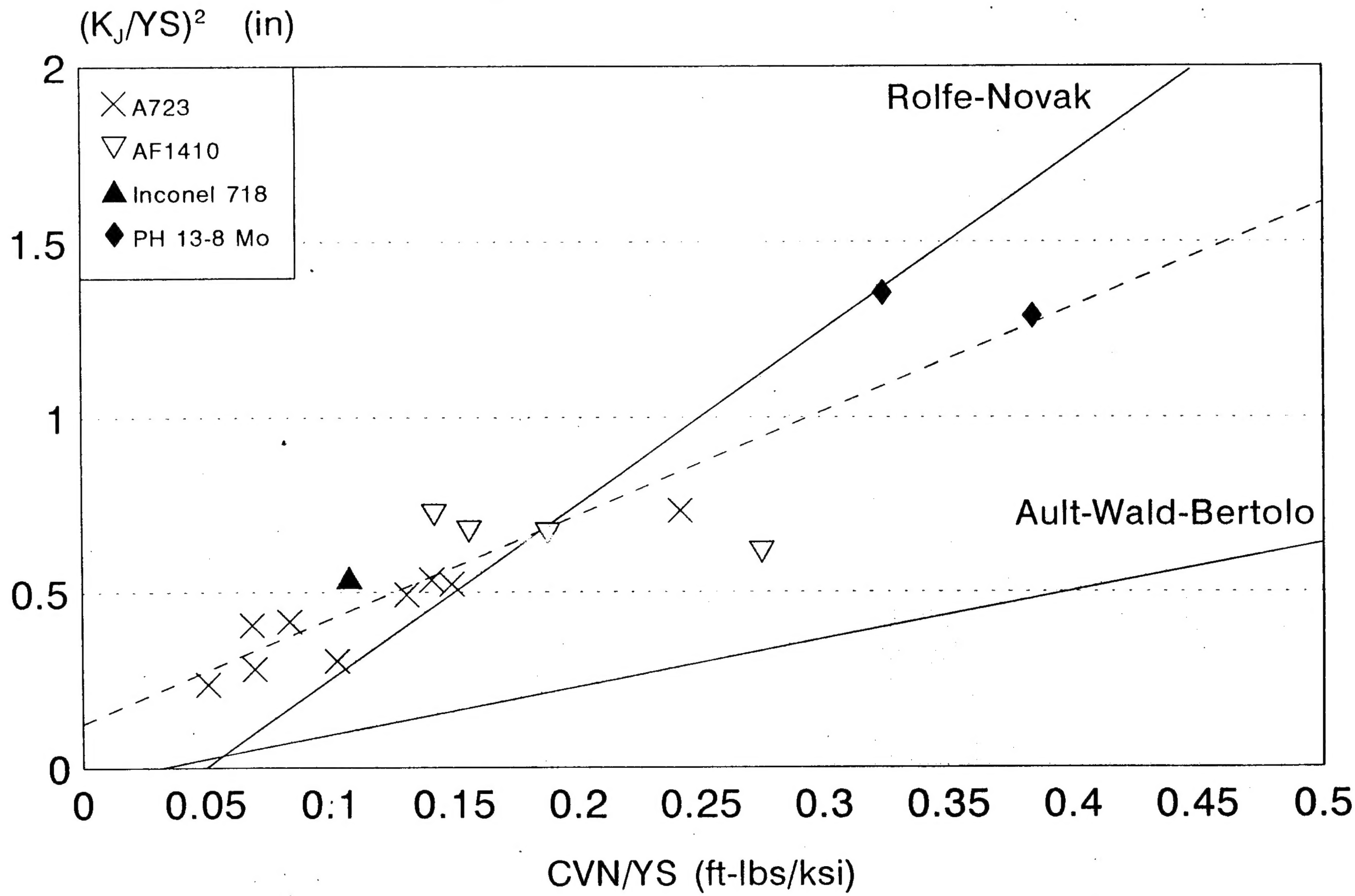

Figure 3 - K_J (72F) vs CVN (-40F)
Solid lines represent correlations, dotted lines represent best linear fit of data being studied

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